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Minimizing operational costs by restructuring the blood sample collection chain☆

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ABSTRACT

This work focuses on improving the structure of a three-echelon blood sample collection chain operated by a health maintenance organization. The chain comprises clinics, where samples are collected from patients; centrifuge centers, where blood is separated into its components; and a centralized testing laboratory, where samples are analyzed. Under the assumption that some clinics can be provided with in-house centrifugation facilities instead of being assigned to centrifuge centers, a problem is formulated for identifying how many centrifuge centers should be established in order to optimally support the collection process. An exact dynamic programming (DP) algorithm and a fully polynomial time approximation scheme (FPTAS) algorithm are designed to solve this problem.

1. Introduction

The current paper focuses on improving the structure of a blood sample collection chain operated by a health maintenance organization (HMO). The blood sample collection chain is a collective term for the stages in which blood samples are collected from patients in clinics, processed, and subsequently submitted for analysis (e.g., detection of antigens, culture and isolation of microorganisms, or DNA sequencing) for the purpose of monitoring patients' health or diagnosing disease. The efficiency of the blood sample collection chain is influenced by changes in healthcare-related demographic and economic conditions, which include population growth, increasing burden of disease, increasing competition among HMOs, and changes in capital expenditure on healthcare. As a result, HMO managers must continually adapt the blood sample collection chain in order to minimize the total costs incurred in the process while maintaining the quality of care. Recent developments in automation of the blood testing process have enabled a large variety of tests to be performed within a short period of time (see Armstrong [1]). These developments have reduced operating costs and have eliminated the necessity of hiring additional staff in times of labor shortage. Given these advantages, current efforts to achieve effective operation of the blood collection chain are focusing mainly on improving "*outdoor*" operations e.g., operations associated with the transportation of samples within the chain and reconsideration of the chain's structure rather than "*indoor*" operations (e.g., analysis procedures). Herein, we focus on the restructuring of a three-echelon blood sample collection chain consisting of clinics; centrifuge centers, where samples are separated into various components in accordance with the requirements of the tests that will be carried out; and a centralized testing laboratory, where the final analysis is carried out. Specifically, we seek to determine the number of centrifuge centers that it is necessary to establish. This problem draws from a real-life scenario in an HMO called *Clalit* (Israel), the second-largest HMO in the world.

Currently, all samples collected from *Clalit* clinics undergo the centrifugation process through a *centralized approach*; that is, instead of being processed in individual clinics, the samples are delivered to designated centrifuge centers (see Fig. 1). The centralized approach is characterized by inflexibility and high dependence on environmental conditions, especially in light of the fact that blood, which is perishable and clots over time, must be delivered to the centers within a specific time span. In particular, the number of blood samples the collection chain can manage is limited by the load the centrifuge centers are able to handle. In order to increase the load capacity of the entire chain, the load capacity of the centrifuge centers would need to be upgraded, or more centers would

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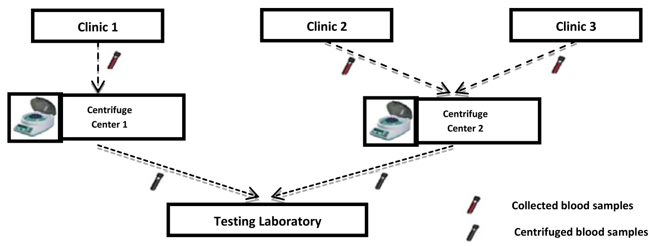

Fig. 1. Centralized approach.

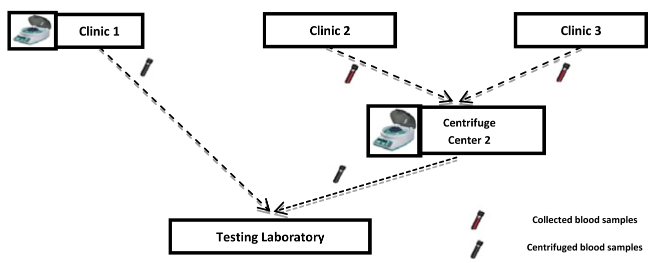

Fig. 2. Integrated approach.

need to be added. This inflexibility is associated with high operational costs. On the other hand, a purely decentralized approach, where each clinic has its own centrifuge device and is able to both collect blood and carry out the centrifugation process, is characterized by a high level of redundancy. In order to overcome the disadvantages of the centralized and decentralized approaches, we propose and analyze a new approach, referred to as the *integrated approach*, in which some clinics are provided with centrifuge devices. Clinics that are not provided with centrifuge devices continue to send collected samples to the centrifuge centers (see Fig. 2). The main objective of this work is to formulate a decision regarding how many centrifuge centers to open in order to maximize the HMO's profit within the constraints of the available budget.

To achieve this purpose, a mixed-integer programming (MIP) problem is formulated. Since the problem is proved to be strongly NP-hard, the solution for large-scale instances cannot be obtained in polynomial time. We therefore adopt some assumptions that enable us to develop an exact pseudo-polynomial dynamic programming (DP) algorithm and a fully polynomial time approximation scheme (FPTAS) to solve the problem in an efficient manner. These algorithms have been successfully applied to data from the existing blood sample collection chain in *Clalit*, and promising results have been obtained.

The remainder of the paper is organized as follows. First, Section 2 presents a comprehensive literature review. The problem statement and a summary of this paper's contribution are given in Section 3. The MIP formulation is presented in Section 4, and then the unique features of the proposed model are described in Section 5. The DP and FPTAS algorithms are presented in Section 6. Section 7 investigates a case study in *Clalit*. At the end of the paper, in Section 8, we draw conclusions and identify potential issues and opportunities associated with further study of the blood sample collection chain.

2. Literature review

In recent years the sample collection chain has been attracting increasing research interest. Works adopting an operational perspective have focused primarily on formulating optimal scheduling and dispatching policies for vehicles deployed for sample collection. Specifically, McDonald [2] and Revere [3] investigated the reengineering of the business process of a laboratory courier service, with the goal of minimizing both the laboratory courier costs and staffing costs for collecting and delivering samples. Yücel et al. [4] considered the "collection for processing" problem, wherein a fleet of vehicles collects samples accumulated at various sites and delivers them to the processing facility. The researchers proposed an MIP model, with the primary objective of maximizing the number of collected items before a defined deadline, and a secondary objective of minimizing total transportation cost. Owing to the intractability of obtaining optimal solutions for such models, even for small instances, Salman et al. [5] proposed a prioritized bi-criteria meta-heuristic algorithm based on a combination of tabu search with linear programming. Recently, Yücel et al. [6] suggested a new heuristic approach to the model suggested by Yücel et al. [4], based on solving the MIP by presenting additional constraints into the model that search for the feasible solutions.

Perusal of the literature suggests that a broad frame of reference for the structure of the blood sample collection chain has not been adequately developed. Most related work comes from the domain of healthcare facility location (FLP) research. This stream of literature includes the work of Calvo and Marks [7], who optimized the location of a health facility system. Price and Turcotte [8] implemented a center-of-gravity model to determine where to establish a blood donor clinic in Quebec. The model was used with a variety of inputs to identify a number of different locations, from which a final choice was made. Hodgson [9] applied a hierarchical location model to primary healthcare delivery in the Salcette region of Goa, India. Jacobs et al. [10] analyzed alternative locations and service areas of American Red Cross Blood (ARC) facilities, where ARC is a three-echelon supply chain consisting of facilities for collecting, testing and distributing blood. The authors used an MIP formulation to identify the optimal ARC structure in terms of the necessary number of facilities and the connections among them. Hodgson et al. [11] used a covering tour model to plan mobile health services in Goa, India. Their model minimized the length of the tour, subject to the constraint that the tour should be less than a certain minimum distance from village centers not visited. Daskin and Dean [12] reviewed the usage of a location set covering model, a maximal covering model and a p-median model (see Hakimi [13,14]) in a healthcare system. Oztekin et al. [15] presented a methodology for optimal placement of a limited number of RFID readers for tracking medical assets in healthcare facilities. The research of Smith et al. [16] dealt with community health projects in northern India and aimed to develop location models specifically designed for healthcare situations in rural areas of developing countries in order to provide affordable and sustainable health services to the poorest people. Since health facilities often provide different levels of service, and also cater to people who reside within different distances from the facilities, the authors implemented a hierarchical modeling approach, where a number of different services are simultaneously located, based on a p-median model. Smith et al. [17] used a variation on the p-median model to locate healthcare facilities according to minimized demand-weighted average travel distance, given a fixed number of p facilities. Different location models and their application to healthcare settings can be found in Berg [18].

In recent years, in light of resource limitations and the high operational costs of healthcare systems, research on preventive healthcare (healthcare that aims to prevent hospitalization and to promote early discharge) has been gaining momentum. Gu et al. [19] considered the Preventive Health Care Facility Location (PHCFL) problem for obtaining optimal locations for preventive healthcare facilities by optimizing the accessibility of preventive healthcare services to population centers. In turn, Rodriguez-Verjan et al. [20] studied the healthcare at home (HAH) facility location–allocation problem with the goal of designing the cheapest dynamic strategic policies for opening and sizing HAH facilities, in order to provide a given territory with healthcare for several pathologies over a long-term time horizon.